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Insect population dynamics and grain damage in small-farm stores in Zimbabwe, with particular reference to *Sitotroga cerealella* (Olivier) (Lepidoptera: Gelechiidae)

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Abstract

Sitotroga cerealella (Olivier) is an important pest of stored grains, whose biology has been well-researched, but little is known about its population dynamics under field conditions. This study examined the importance of the moth in relation to other storage insect pests on maize and sorghum under smallholder conditions in Zimbabwe. On sorghum heads, *S. cerealella* and *Rhyzopertha dominica* F. were dominant, but *Sitophilus* spp. were dominant on both maize and sorghum grain bulks. The insects themselves and associated grain damage were mostly confined to the top 30 cm of such bulks. An exception was *R. dominica*, which occurred in large numbers at lower grain levels. The implications of these findings are discussed with reference to reduced pesticide use through more-targeted grain treatment in tropical small-farm stores.

Keywords: Spatial and temporal distribution; Population dynamics; Stored grain; Grain damage; *Sitotroga cerealella*; *Rhyzopertha dominica*; *Sitophilus* spp.

Introduction

Studies of insect population dynamics under field conditions are important in developing appropriate pest-management strategies. Most studies of interactions between *Sitophilus* spp. and *Sitotroga cerealella* (Olivier) have been confined to the laboratory (Ayertey, 1976; Shazali, 1982), but the results are of only limited value, because on-farm environmental conditions fluctuate, and natural enemies and other storage insect pests exert their influence on the development and behaviour of these two pests. Detailed ecological studies of tropical storage pest complexes, dominated by *Sitophilus* spp. and *S. cerealella,* were made by Giles (1964) on sorghum (threshed and unthreshed) and on maize cobs by De Lima (1978) and Markham (1981), but in Zimbabwe, most sorghum and maize are dried and threshed before storage. The storage facilities used in the aforementioned studies allowed free natural ventilation, whereas in Zimbabwe, brick or pole and mud-plastered stores, referred to as closed stores, are commonly used. This is different from many other sub-Saharan African countries where the bulk of cereals are stored unthreshed. Consequently, there are few studies which have investigated the interactions of pest complexes on threshed grain, especially sorghum, stored in closed small-farm stores.

The study reported here investigated grain damage due to storage insects, and distribution of the insects, in grain stored in small-farm stores in two contrasting agro-ecological zones in Zimbabwe. The specific objectives of this study were:

- to quantify spatial and temporal insect grain damage in small-farm stores; and
- to investigate spatial and temporal distribution of storage insects in small-farm stores, with particular reference to *S. cerealella, Sitophilus zeamais* (Motschusky), *Sitophilus oryzae* (L.) and *Rhyzopertha dominica* (F.). *Sitophilus* spp. and *R. dominica* share the same ecological niche as *S. cerealella* in stores and therefore there is potential for competition between these species.

Materials and Methods

Experimental sites, timing and store types

The study was carried out in two contrasting agro-ecological zones of Zimbabwe: at Kulima Mbobumi Training Centre (KMTC), Binga District in the Zambezi Valley; and at the Institute of Agricultural Engineering (IAE), located at Hatcliffe Farm in Harare. KMTC represented typical hot and dry conditions, whereas IAE was cool and sub-humid (Fig. 1a,b).

The experiments were conducted over 32 or 44 weeks in the 1998–99 (Year 1) and 1999–00 (Year 2) storage seasons, respectively, in Binga, while in Harare the periods were 36 (1998–99) or 48 weeks (1999–00). The experiments began in August or September of each year.

Grain was stored in brick granaries compartmentalised into six bins (each bin measuring 0.60 × 0.60 × 1.65 m deep), constructed at KMTC and at IAE specifically for this study (Fig. 2).

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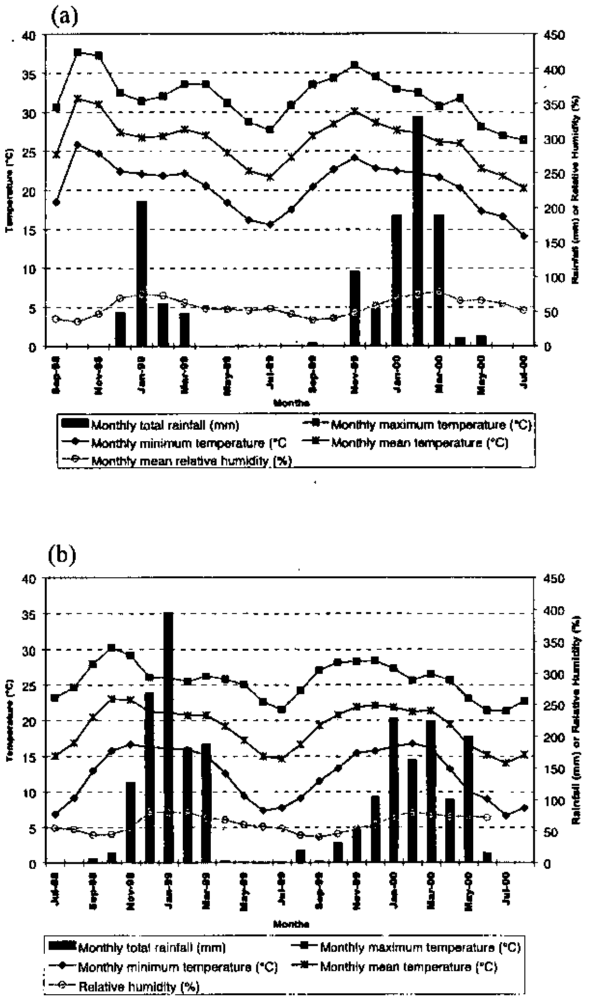

Source: Department of Meteorological Services, Zimbabwe

Fig. 1. Meteorological data from (a) Binga main centre (b) Harare Main Office

Fig. 2. The experimental store (composed of 6 bins) used in Binga district and Harare.

Four stores were used in the experiments in Binga and two in Harare. The bins were left open to facilitate regular sampling and to allow free access to the grain by insects. Before commencement of the second storage season, the store interior was thoroughly cleaned and re-plastered with mud to eliminate residual insect infestation.

Grain type and quantity stored, storage period and artificial infestation

Grain damage by storage insects and distribution of the insects in stored grain was investigated on both threshed (bulk) and unthreshed (heads) sorghum. Smallholder farmers in the Binga District commonly store both forms of sorghum (Douglass et al., 1997). In Harare, only bulk maize was used, because in most parts of Zimbabwe where maize is widely grown, it is commonly stored shelled rather than on the cob (Mvumi et al., 1995). White, dent, threshed hybrid maize, variety R215 (180 kg/bin in Year 1) or SC621 (275 kg/bin in Year 2) were used in Harare, while improved threshed sorghum, variety SV2, 300 kg/bin in Year 1 and 327 kg/bin in Year 2 was used in Binga. The unthreshed sorghum was not weighed, but bins with both maize and sorghum were filled 100–120 cm deep. Before store loading, the grain was fumigated with phosphine at 21 g/m^3 (according to the manufacturer's recommendation). Each experimental store was seeded with 200 adult specimens of *S. cerealella* and *S. oryzae* or *S. zeamais* to boost initial infestation. In Year 2, adult *R. dominica* were included in the Binga releases, after Year 1 observations showed that it was an important pest of sorghum. The number of each species was increased to 500 and they were introduced into each bin rather than the whole store.

Experimental layout, treatments and sampling frequency

IAE, Harare

Two stores were used in Year 1, and in each store 4 bins were loaded with shelled maize, sampled at 4-weekly intervals. Another bin containing shelled maize was reserved to house temperature sensors. A similar set-up was used in Year 2, except that the number of bins in each store was increased to 5.

KMTC, Binga

In Year 1, 4 stores were used with 3 treatments replicated once in each store. The treatments and sampling frequencies were: (1) threshed sorghum sampled at 4-weekly intervals without replacement (i.e. grain removed was not put back into the store after examination); (2) sorghum heads sampled at 4-weekly intervals with replacement (i.e. heads put back into the store after examination); and (3) sorghum heads sampled at 4-week intervals without replacement.

In treatments 1 and 3, sorghum was destructively sampled and, after analysis, discarded (i.e. sampling without replacement). In treatment 2, samples were returned to their respective positions after analysis to allow observations and analysis on the same grain throughout the storage season (i.e. sampling with replacement). Two bins (one containing bulk grain and another heads) were set aside in two of the stores to house temperature sensors. All the treatments were randomly allocated to the bins in each store and the stores themselves were regarded as single plots.

Year 2 treatments were as follows: (1) threshed sorghum, sampled at 4-weekly intervals without replacement; and (2) sorghum heads, sampled at 4-weekly intervals with replacement. Temperature sensors were set as in the previous season.

Sampling techniques

Bulk grain (maize and sorghum)

Bulk grain was sampled using a 1.27-m brass multi-compartmented probe (with 8 sampling ports) which was inserted vertically into the grain at approximately the same positions at each sampling occasion. Two ports were blocked such that grain could be sampled independently from 3 different depths using 2 ports at the top, 2 ports in the middle and 2 ports at the bottom. Each pair of sampling ports covered a length of 22 cm along the probe and the pairs were inter-spaced by 8 cm.

When filled with grain, each bin was stratified into an arbitrary 27-cube grid to match the positions of the probe ports vertically and horizontally. Samples were collected by probing vertically at two diagonally opposite bin edges (proximal and distal respectively) and at the centre of each bin to give samples from the top, middle and bottom layers for each sampling position. At sampling, a wooden sampling frame was placed horizontally over the bin to give guidance on the sampling positions. The positions gave a total of 3 samples per probe, each of 70–100 g or a total of 600–900 g of grain per bin. Each sample of 70–100 g was packaged and analysed separately.

Sorghum heads

As part of the development of a suitable sampling technique, samples were placed into two types of containers. In bins from which heads were removed for analysis and not replaced (treatment 3, at KMTC), heads were placed in 8 chicken-wire mesh baskets in each bin. At store loading, the samples were randomly allocated to pre-determined sampling dates so that at each sampling occasion, one basket was removed from each bin using a metal wire attached to it. In year 1, the baskets were randomly placed in each bin and collection of some of the samples was awkward due to their location in the bin. The sampling technique also disturbed the micro-environment in the store bin and, therefore, in year 2, this treatment was excluded. However, the treatment did provide data on insect population changes over time but not spatial distribution.

Where heads were put back into the bin after sample examination (treatment 2), they were contained in specially designed cages which had both an inner frame (17 cm diameter and 30 cm height) and a separate outer frame (≈ 1 m high) (Fig. 3). The outer frame remained permanently in position in the bin and maintained the integrity of the bulk of heads intact. The inner frame was removed at each sampling occasion and contained the heads to be examined. After examination, the heads were replaced into the respective inner frame, which was then placed back into the store in its original position. Three such inner frames (corresponding to top, middle and bottom samples) were stacked vertically one above the other at the centre of the bin.

The sorghum head samples were analysed on-site. During analysis, the insects were gently shaken out of each sorghum head into a polythene bag. Mobile insects, such as adult moths, were identified, extracted with a glass pooter attached to a vacuum pump and counted. The remainder of the insects were sieved from the grain/trash mixture using nested sieves (1.70 mm and 710 μm apertures), identified and counted. The tray rims were coated with fluon to prevent insects from crawling out during sample analysis. For sluggish insects like *R. dominica*, samples had to be re-sieved several times to collect individuals embedded in the grain.

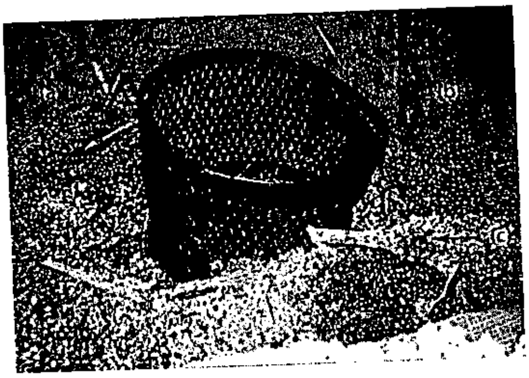

Fig. 3. The design of cages containing unthreshed sorghum and their positioning in the store compartment: (a) outer frame; (b) inner frame containing the sample of unthreshed sorghum; (c) unthreshed sorghum in the rest of the store compartment. The frame holes measured 10 mm × 20 mm.

At the end of the analysis, the sample plus the corresponding insects and frass for each segment were returned to their respective cages. The active fliers (wasps and moths) were chilled in a freezer for 2–3 minutes before returning them directly into the corresponding cage, itself having been already placed in its position within the bin. The heads were returned into the cage in the approximate reverse sequence into which they had been removed. After the insect counts, sorghum heads which were not being replaced in the store (treatment 3) were carefully threshed, the grain weighed and corresponding insect numbers from the sample converted to a standard grain mass by simple proportion. Heads that were replaced were processed in this way only at the end of the storage season.

Data collected

The data collected included percentage insect damaged grain, arthropod fauna population, F1 emergence upon incubation of samples at 28 ± 2°C and 75 ± 5% r.h. for 5 weeks, and grain temperature (using thermistors and a Delta-T data logger).

Data analysis

To determine the effects of the different sampling positions, data were subjected to analysis of variance (ANOVA) using Genstat 5 for Windows 95 (Anon., 1998). Insect numbers were transformed to $\log_{10}(x+1)$ where x = the number of insects per unit mass of grain. Arcsin (p) and $\sqrt{(p+0.5)}$ transformations were used on maize and sorghum grain damage values, respectively, where p = percentage insect damaged grain (Gomez and Gomez, 1984). Parameters showing significant differences after the initial ANOVA were further compared using the least significant difference

(LSD) test. Three-dimensional graphs showing variation in grain damage or insect numbers with grain depth or proximity to bin edges over time together with temperature, assisted in data interpretation. In both years 1 and 2 no direct comparisons were made between threshed and unthreshed sorghum because of the different sampling techniques used. Comparison was only within each treatment.

Results

The spectra of arthropods found at the two research sites during the two storage seasons are shown in Table 1, but henceforth the results will mainly focus on the major species.

KMTC, Binga: Year 1

Threshed sorghum: insect dynamics and distribution

The insect populations of the various species remained low until week 24, when differences were observed. *S. oryzae* increased dramatically from week 24 and became the most dominant species until the end of the experiment (Fig. 4). The *S. cerealella* population was insignificant until week 20 when it increased to a peak of 35 insects/kg.

S. oryzae and *S. cerealella* showed a strong preference for the top grain layers in threshed sorghum compared with *R. dominica* which occurred in the middle and bottom grain layers in relatively large numbers (Figs 5–7). Within the top layer, insect populations began increasing from week 16

Table 1. Spectrum of storage insects found on sorghum and maize during the two storage seasons at each site.

Insect species	Binga (Sorghum)		Harare (Maize)
	Threshed	Unthreshed[a]	Threshed
Sitophilus oryzae (L.) (Coleoptera: Curculionidae)	*	*	
Sitophilus zeamais (Motschulsky) (Coleoptera: Curculionidae)			*
Rhyzopertha dominica (F.) (Coleoptera: Bostrichidae)	*	*	
Tribolium castaneum (Herbst) (Coleoptera: Tenebrionidae)	*	*	*
Gnatocerus cornutus (F.) (Coleoptera: Tenebrionidae)			*
Gnatocerus maxillosus (F.) (Coleoptera: Tenebrionidae)			*
Oryzaephilus surinamensis (L.) (Coleoptera: Silvanidae)	*	*	
Lasioderma serricorne (F.) (Coleoptera: Anobiidae)	*	*	
Cryptolestes ferrugineus (Stephens) (Coleoptera: Cucujidae)	*	*	*
Carpophilus spp. (Coleoptera: Nitidulidae)	*	*	
Sitotroga cerealella (Olivier) (Lepidoptera: Gelechiidae)	*	*	*
Plodia interpunctella (Hübner) (Lepidoptera: Pyralidae)			*
Corcyra cephalonica (Stainton) (Lepidoptera: Pyralidae	*		
Xylocoris spp. (Hemiptera: Anthocoridae)	*	*	
Anisopteromalus calandrae (Howard)[b] (Hymenoptera: Pteromalidae)	*	*	*
Liposcelis spp. (Pscocoptera: Psocidae)		*	

[a] Mites, ants (Formicidae) and a hemipteran bug were also found but not identified

[b] Possible that there were many species but only one was positively identified

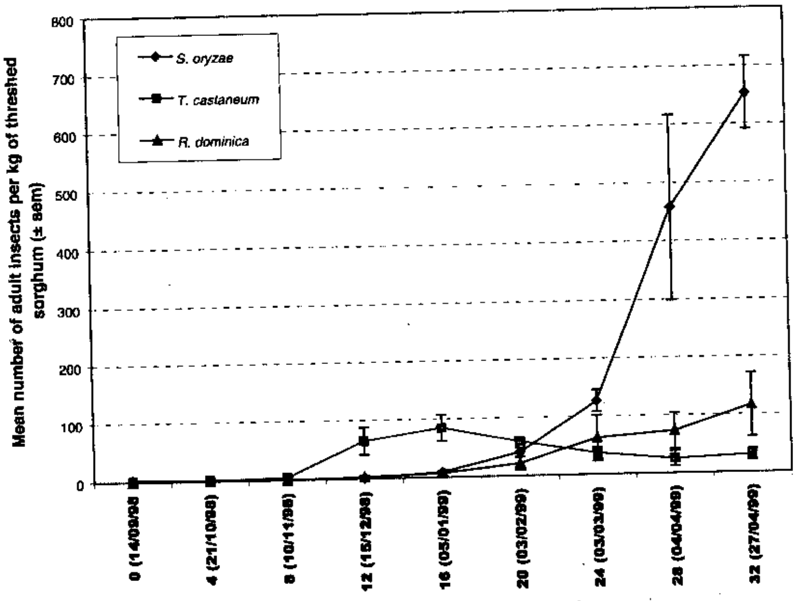

Fig. 4. Mean total number of major adult insects on threshed sorghum (all sampling positions) sampled from Binga stores (year 1; $n = 4$)

onwards and *S. oryzae* was the most numerous species, becoming dominant after week 24, while *R. dominica* and *S. cerealella* were present in only modest numbers from week 24 onwards (Fig. 8).

Highly significant differences in total insect pest populations ($p < 0.001$) were found among the grain layers, with the top layer having the highest population and the bottom the lowest. The position of grain in relation to the sides and middle of the store had no effect on insect population until the end of the storage period.

F1 emergence from threshed sorghum

Insect pest emergence at F1 was concentrated in the top grain layer, with *S. oryzae* being the dominant species (Fig. 9). Most of the downward dispersal of *S. oryzae* occurred towards the end of the storage period. Although only low numbers (< 10 insects/100 g) of *R. dominica* emerged from the samples (Fig. 10), the F1 distribution pattern showed a capacity to infest and oviposit in all grain levels. *Sitotroga cerealella* infestation was evident only in February when F1 emergence suddenly rose to a peak (Fig. 11).

Grain damage by insects in threshed sorghum

Throughout the 32-week storage period, grain damage was restricted to ≤ 10% in the middle and bottom samples, whereas in the top samples it was up to 40% (Fig. 12). Damage levels in grain samples from the different vertical positions were highly significant ($p \leq 0.003$), but the location of sampling position in relation to the sides or centre had no effect on damage levels. Damage was significantly greater in the top layer, but in the middle and bottom layers it did not differ.

Unthreshed sorghum (sampled with replacement): insect dynamics and distribution

Irrespective of sampling depth, abundance of the primary insect pests was in the order *R. dominica* > *S. cerealella* > *S. oryzae*. Both *R. dominica* and *S. cerealella* populations increased rapidly from week 24. The latter declined after week 28, while the former continued to increase. *Rhyzopertha dominica* tended to prefer the bottom layers, although present at all vertical positions, whereas *S. cerealella* showed no particular preference for any depth (Fig. 13). Large numbers of ants (Formicidae) were recorded in the head samples in early March (week 24)., and were observed attacking adult *S. cerealella* in particular.

No differences in total pest population were found among the grain layers. However, differences among individual species numbers were highly significant ($p < 0.001$), starting from week 20 until the end of the experiment. Further comparison among species showed that the *S. cerealella* population was higher than that of *S. oryae* up to week 32. The *S. cerealella* population was higher than, or the same as, that of *R. dominica* until week 32, when the bostrichid became the most abundant insect.

Unthreshed sorghum (sampled without replacement): insect dynamics and distribution

Sitotroga cerealella was the most dominant species, followed by *R. dominica*, whereas *S. oryzae* was among the least common insects (Fig. 14). *S. cerealella* reached a maximum population in March then began declining (after 24 weeks of storage).

F1 emergence from unthreshed sorghum sampled without replacement

Sitotroga cerealella dominated the storage insect population, reaching a peak at week 28, then declining (Fig. 15). The *S. oryzae* population was low throughout the storage duration.

Grain damage by insects in unthreshed sorghum (sampled without replacement)

The damage level started increasing in week 16 and rose sharply to nearly 30% (Fig. 16). The trend of grain damage in the unthreshed grain was very similar to that obtained in the top layer of threshed grain though the maximum damage recorded there was about 40%.

KMTC, Binga: Year 2

Threshed sorghum: insect, dynamics and distribution

In year 2, *S. oryzae* and *R. dominica* were the most numerous insect species; a trend noticeable after 16 weeks of storage (Fig. 17). From week 20, *S. oryzae* increased rapidly, whereas the *R. dominica* multiplication rate was more gradual. *Sitotroga cerealella* was the least numerous of the pests, the population remaining at ≤10 insects/kg. The distribution pattern of insect species was similar to that in year 1 although the insect numbers were generally greater. However, more insects were recorded than in Year 1.

Total insect pest populations found at different grain depths were significantly different ($p \leq 0.016$) from week 20 onwards in the 4 stores. The effect of sample location in relation to the sides and centre of the compartment was inconsistent, more so with respect to *R. dominica*. In vertical comparisons, the LSD test showed significant differences between the top and bottom grain layers whereas the middle and the bottom layers tended to show no significant differences between them in most of the samplings. Where significant differences were found in the horizontal positions, the corner positions were not significantly different and the two positions generally had significantly higher insect populations compared with the centre position. In the top layer, *S. oryzae* dominated from week 16 onwards while *S. cerealella* was relatively insignificant (Fig. 18)

F1 emergence from threshed sorghum

As in year 1, the composition of emerging species was dominated by *S. oryzae* while *R. dominica* and *S. cerealella* populations were not significant (Fig. 19). Most *S. oryzae* and *S. cerealella* F1s emerged from the top grain layer, whereas with *R. dominica* positional effects were not evident.

Grain damage of threshed sorghum by insects

The grain damage pattern was similar to that observed in year 1. However, higher damage levels were recorded in the middle and bottom layers (up to 30% compared with less

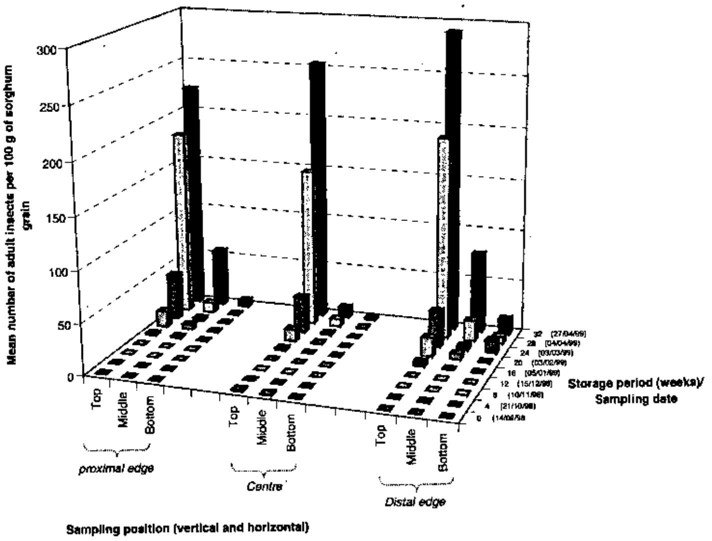

Fig. 5. Mean total number of *S. oryzae* in threshed sorghum sampled from 3 horizontal positions and 3 depths in Binga stores (year 1; *n* = 4)

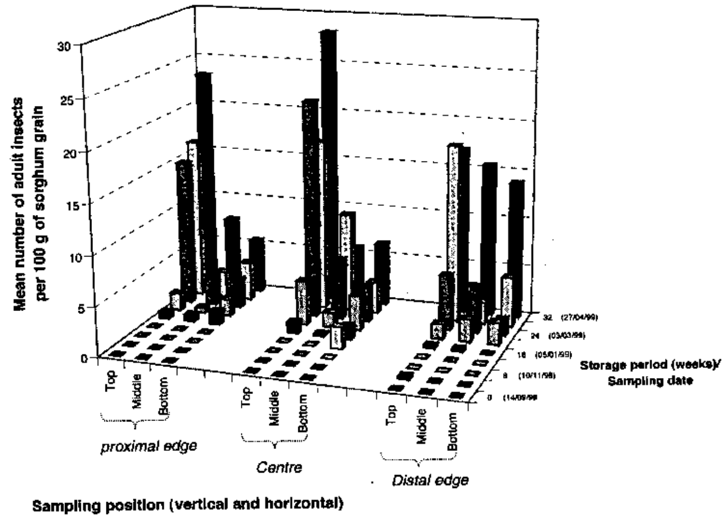

Fig. 6. Mean total number of *R. dominica* in threshed sorghum sampled from 3 horizontal positions and 3 depths in Binga stores (year 1; *n* = 4)

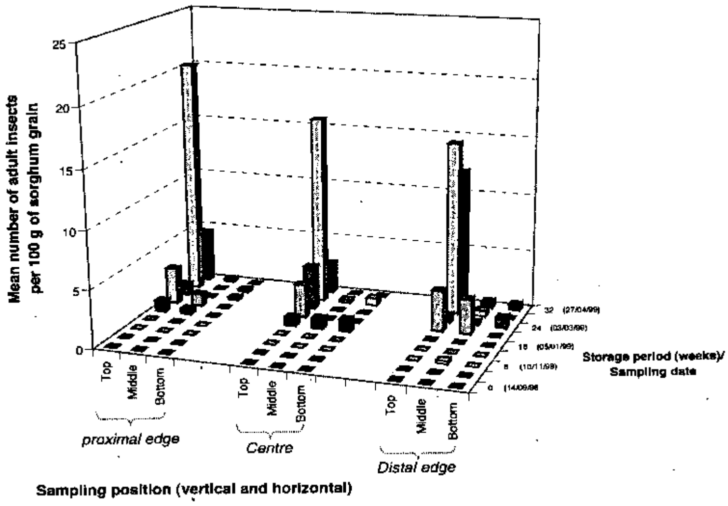

Fig. 7. Mean total number of *S. cerealella* in threshed sorghum sampled from 3 horizontal positions and 3 depths in Binga stores (year 1; *n* = 4)

than 10% in year 1) in the last 8 weeks of storage. In all 4 stores, samples from the vertical positions showed significant differences in grain damage (range $0.012 \le p \le 0.040$, but a p-value of ≤ 0.001 was most common). A significant edge effect was rare. Significant differences were found mainly between top and bottom layers.

Unthreshed sorghum: insect spectrum, dynamics and distribution

Rhyzopertha dominica dominated for the first 32 weeks of storage, after which *S. oryzae* superseded the bostrichid (Fig. 20). The *S. oryzae* population rose steeply after 32 weeks of storage to >2500 insects/kg of sorghum whereas *R. dominica* reached a plateau at <500 insects/kg. At the end of the storage period, the *S. cerealella* population suddenly exploded, exceeding that of *R. dominica* but still less than *S. oryzae*. Although *S. oryzae* and *S. cerealella* did not show preference for any particular depth, *R. dominica* showed a preference for the bottom layer (Fig. 21). No significant differences were found in total insect pest populations amongst the unthreshed sorghum layers.

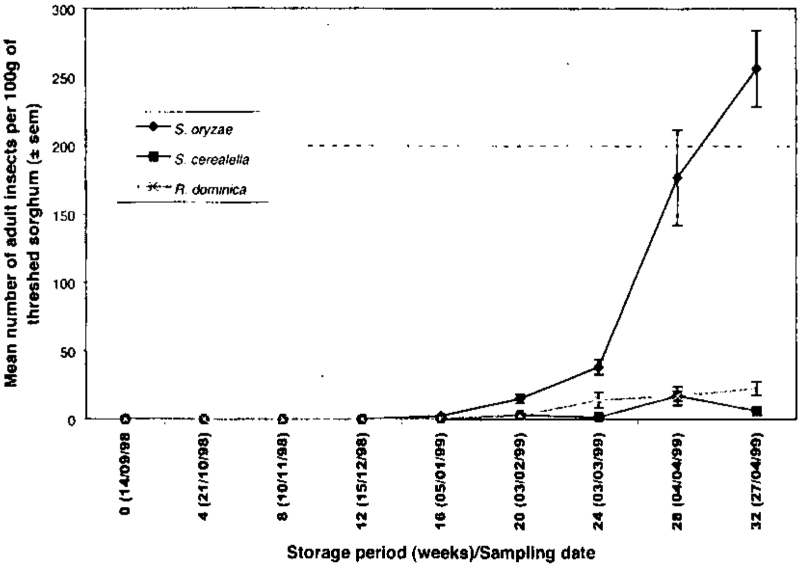

Fig. 8. Mean number of adult insects on threshed sorghum sampled from the top grain layer in Binga stores (year 1; $n = 12$)

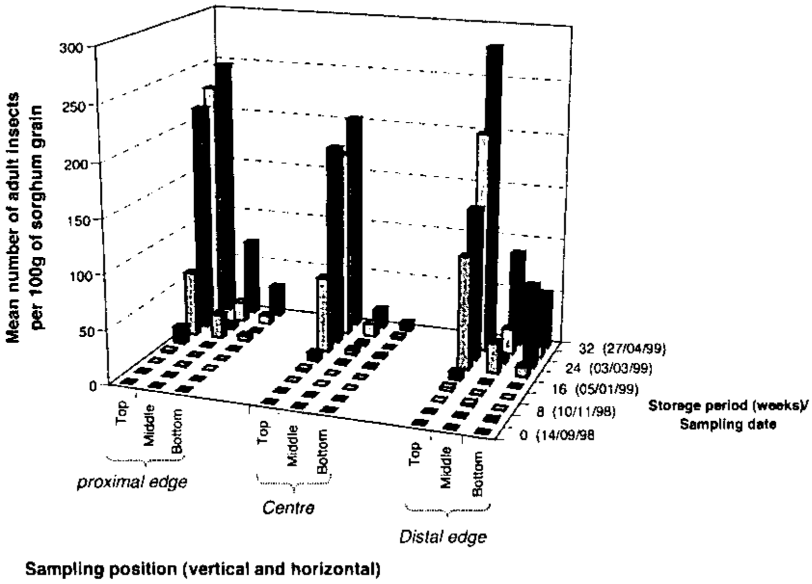

Fig. 9. Distribution of F1 *S. oryzae* (after a 5-week sample incubation) at 3 horizontal sampling positions and 3 depths on threshed sorghum stored in Binga (year 1; $n = 4$)

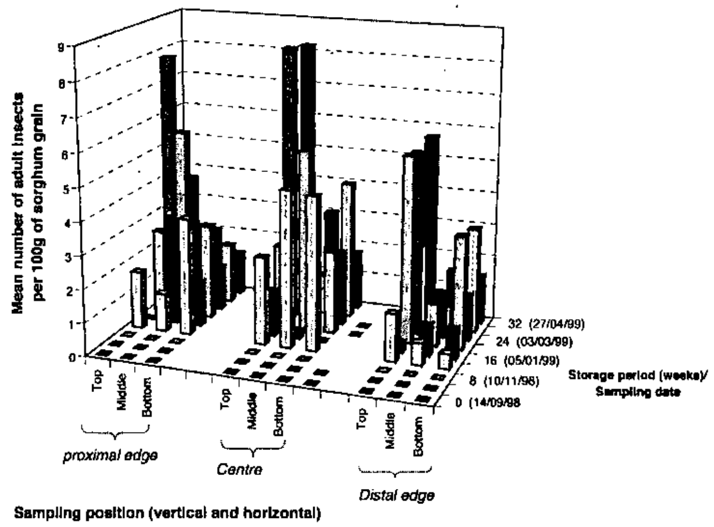

Fig. 10. Distribution of F1 *R. dominica* (after a 5-week sample incubation) at 3 horizontal sampling positions and 3 depths on threshed sorghum stored Binga (year 1; *n* = 4)

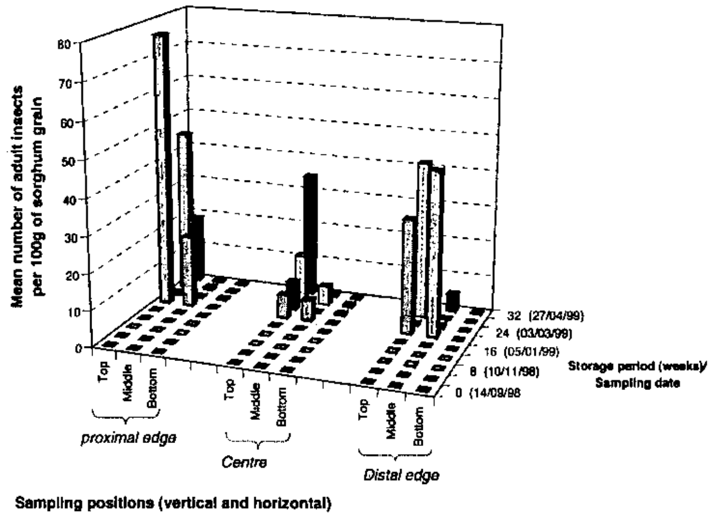

Fig. 11. Distribution of F1 *S. cerealella* (after a 5-week sample incubation) at 3 horizontal sampling positions and 3 depths on threshed sorghum stored in Binga (year 1; *n* = 4)

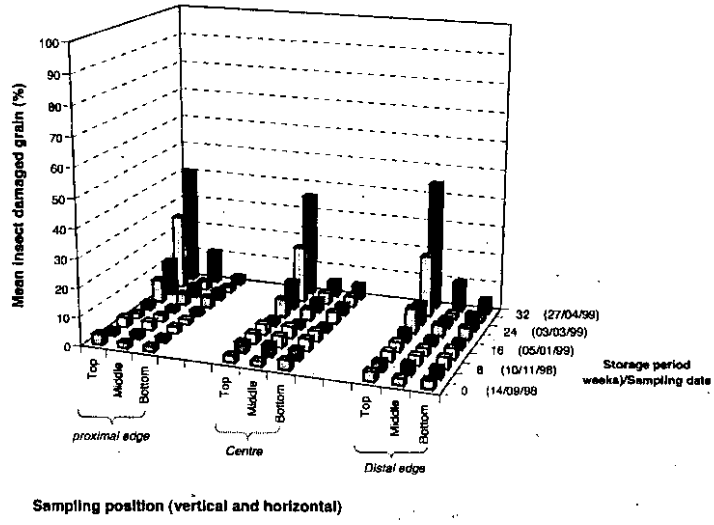

Fig. 12. Mean percentage of insect-damaged sorghum grain (threshed) sampled from 3 horizontal positions and 3 depths in Binga stores (year 1; *n* = 4)

IAE, Harare: maize, Year 1

Insect dynamics and distribution

The pest complex was mainly dominated by *S. zeamais*, but from 28 weeks onwards the *T. castaneum* population increased rapidly to catch up with *S. zeamais* by the end of the experiment (Fig. 22). The highest numbers of *S. cerealella* (10 insects/kg) were recorded after 20 weeks whereas the *S. zeamais* population kept increasing up to the end of the experiment in June (week 28).

Most of the storage insect pests occurred in the top layer of maize (Fig. 23), and *S. zeamais*, *Tribolium castaneum* and *S. cerealella* constituted the main species found in this layer. *Sitophilus zeamais* was the most numerous insect in the top layer, exceeded only by *T. castaneum* at week 28. Its population increased sharply to more than 500 insects/100 g by the end of the storage period, compared with about 300 *S. zeamais*/100 g at the same time. The population of *S. cerealella* was relatively insignificant (Fig. 24).

Strongly significant differences in total insect pest numbers ($p < 0.001$) due to depth were found from week 20 onwards. There was no significant difference between total numbers found at the edges of the compartments and at the centre, but there were differences among the grain layers.

F1 emergence after sample incubation

Both *S. cerealella* and *S. zeamais* F1 populations increased at about the same rate for the first 12 weeks then *S. zeamais* increased exponentially to more than 400 insects/kg by week 20 (Fig. 25). The *S. cerealella* population declined at week 16, followed by eventual disappearance of the moth after week 24, coincided with a rise in the adult *T. castaneum* population in the top grain layer.

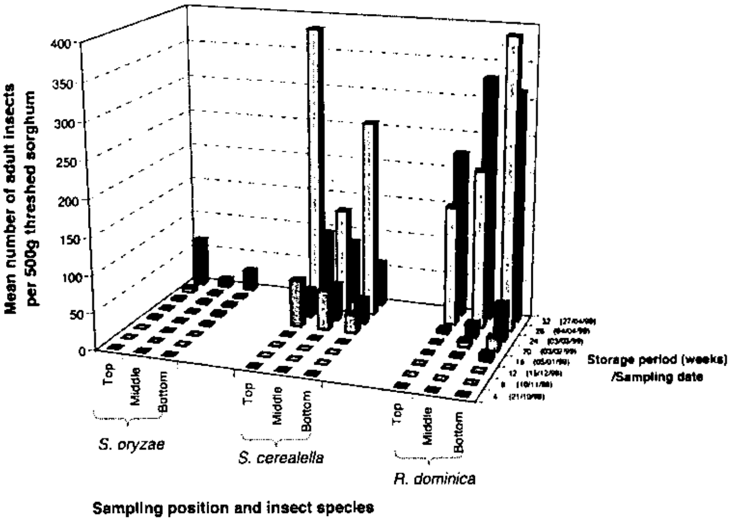

Fig. 13. Distribution of major insect pests on unthreshed sorghum sampled from 3 depths in Binga stores (year 1; $n = 4$)

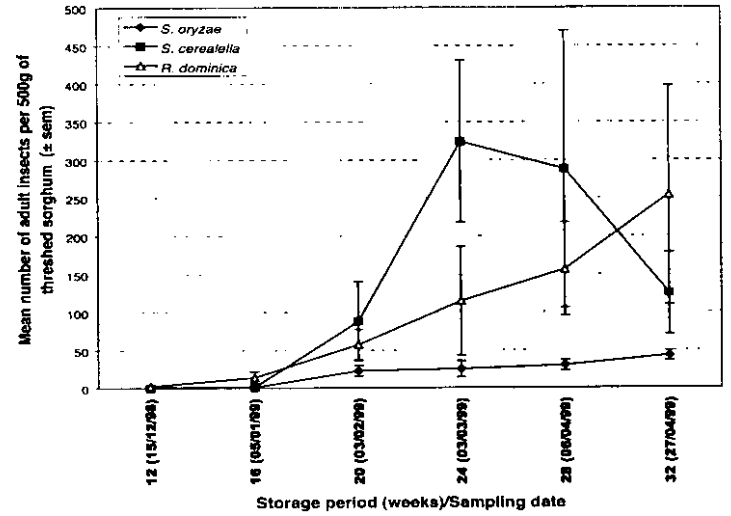

Fig. 14. Population development of major insect pests in unthreshed sorghum sampled (without replacement) from stores in Binga (year 1; $n = 4$)

Grain damage of threshed maize by insects

Samples from the top layer sustained higher damage levels than the middle and bottom layers (Fig. 26). The concentration of grain damage in the top layers was consistent throughout the 36-week storage period. The damage level in the top layer started rising sharply after 16 weeks of storage and rose exponentially to > 80% by week 24, whereas that of the middle layer lagged by 4 weeks and rose at a slower rate. Grain damage in the bottom layer increased most slowly to a maximum of ≤ 30% during the 36-week storage period.

The differences among the vertical positions were highly significant ($p \leq 0.005$) from 12 weeks onwards, whereas the effect of proximity to compartment walls was evident from week 20 ($p \leq 0.003$) though erratic in the remaining storage period. The grain in the top layer sustained significantly greater damage ($p \leq 0.001$) than that in the bottom layers. Damage at different vertical positions reflected the insect distribution. No discernible trend was evident in the horizontal positions.

IAE, Harare: maize, year 2

Insect dynamics and distribution

During year 2, in the middle and bottom layers of the compartment at the centre position the insect population remained low compared with the same layers in the edge positions, and a propensity for aggregation in the top layers by most storage insect species was found. However, an increased population of *S. zeamais* was found in the middle and bottom layers of peripheral samples during the last 12 weeks of storage (Fig. 27).

Differences in total insect-pest population among the vertical positions were highly significant ($p < 0.001$) from week 20 onwards, while the horizontal positions showed significant differences ($p \leq 0.044$) from week 24 until the

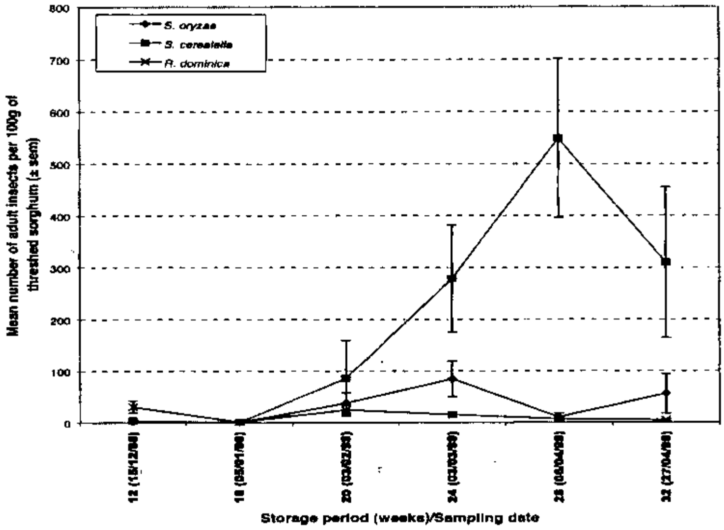

Fig. 15. Mean number of adult F1 insects (after a 5-week incubation of subsamples) from unthreshed sorghum sampled without replacement from farm-stores in Binga (year 1; $n = 4$)

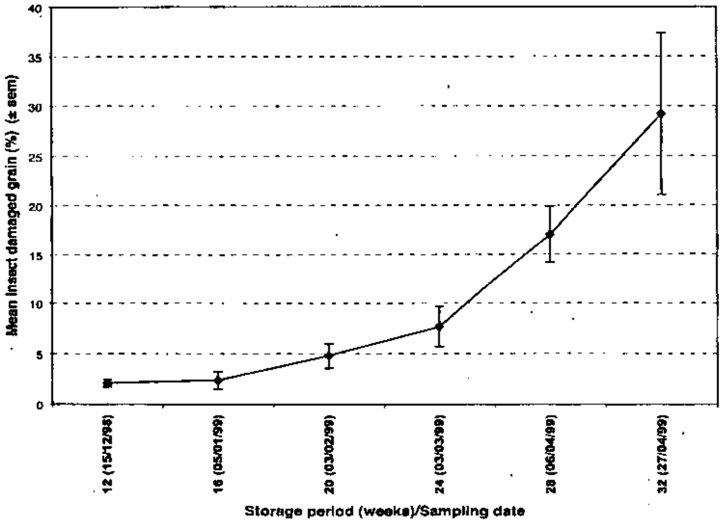

Fig. 16. Mean percentage of insect-damaged sorghum grain (unthreshed) sampled from small-farm stores in Binga (year 1; $n = 4$)

end of the storage period. There were no significant differences between the bottom and middle layers, whereas each of these two layers had significantly lower pest populations than the top layer. The populations of *S. cerealella* and parasitic wasps were very low (< 2.5 insects/kg).

F1 emergence after sample incubation

The *S. zeamais* population built up rapidly within the first 16 weeks of storage and thereafter it stabilised (Fig. 28). The *S. cerealella* population was negligible when sampling depth is disregarded. The emergent insect-pest population was concentrated in the top grain layer and followed an infestation pattern similar to the insect counts obtained at sample analysis. The dominance of *S. zeamais* infestation in the top layer was less pronounced on the edges of the compartment compared with the centre (Fig. 29). *Sitotroga cerealella* was present in very low numbers (≤ 5 adult insects per 100 g) and no particular trend was discernible.

Grain damage by insects

The grain damage pattern was similar to that of year 1, with most damage occurring in the top layer throughout the 48-week storage period.

Discussion

Interaction of *Sitotroga cerealella* with *Sitophilus* spp. or *Rhyzopertha dominica*

Sitotroga cerealella was dominant on unthreshed sorghum. Its success maybe attributed to the availability of ample head space for mating and movement in search of oviposition sites. That no significant differences in insect population were obtained among the three depths of unthreshed sorghum, supports the supposition that movement is much more easy than in densely packed threshed grain.

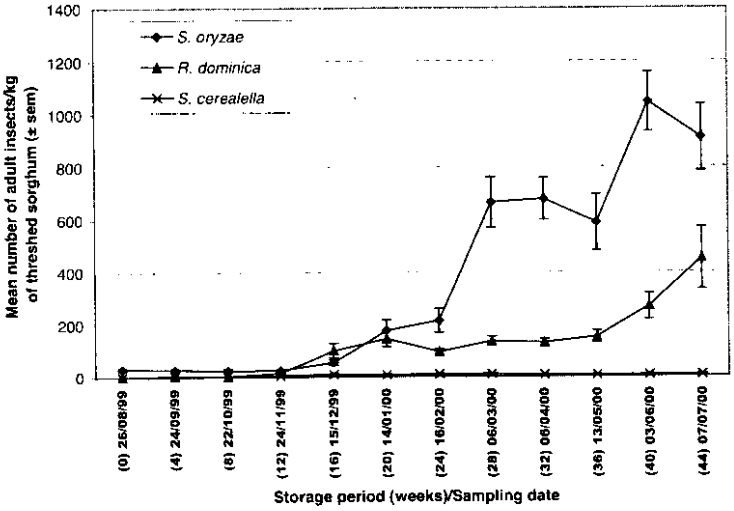

Fig. 17. Mean total number of major adult insects on threshed sorghum (all sampling positions) sampled from Binga stores (year 2; $n = 10$)

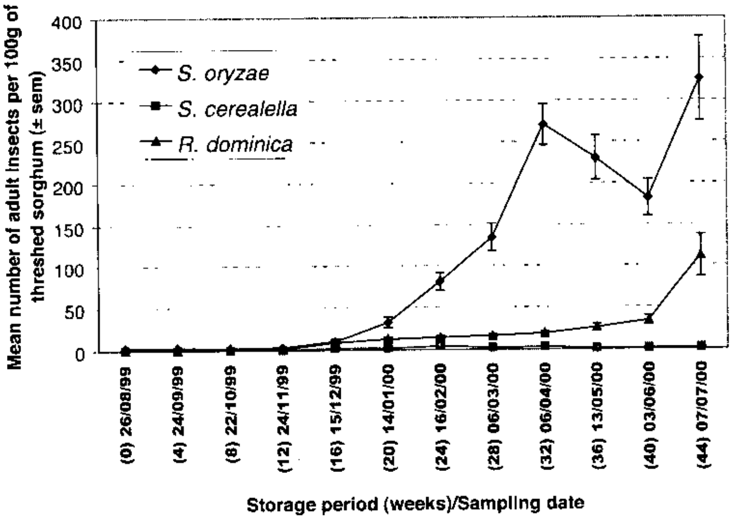

Fig. 18. Mean number of adult insects on threshed sorghum sampled from the top grain layer in Binga stores (year 2; $n = 30$)

On threshed sorghum, *S. cerealella* was found mainly in the top layer, but was completely dominated by *S. oryzae*, whereas *R. dominica* was found in relatively large numbers in the middle and bottom layers. In comparison to *Sitophilus* spp., *S. cerealella* can be regarded as insignificant on threshed grain. The insect is fragile and unable to penetrate densely packed grain, which limits its activities such as mating and oviposition (Muhihu, 1984). The restriction of *S. cerealella* to the top grain layer is adversely affected by both intra- and inter-specific competition in that zone. Upon emergence from kernels, the adult requires free space to open its wings to render them functional (Simmons and Ellington, 1933) and this would be difficult in threshed grain, especially when the grain size is small.

The high insect infestation pressure recorded in the top layer could be detrimental to *S. cerealella* immature stages. As they crawl over grain, adult beetles can trample the eggs of the moth, which are laid on the outside of grains and the feeding activity of the adult weevils can also mechanically damage the developing larvae or interfere with larval development in the grain kernels (Chesnut and Douglas, 1971). Because of the extended longevity of adult *Sitophilus* spp. and *R. dominica*, the beetles continue laying eggs during their entire lifespan and can therefore build up large populations over time, whereas the adult moth is short-lived, resulting in discrete generations. In maize grain, *S. cerealella* was found to be better able to develop in damaged grain than is *S. zeamais* (Arbogast and Mullen, 1987), which should give the moth a competitive advantage over the beetle. However, in the current study, this was not manifested, probably due to parasitism and predation.

In the absence of its natural enemies, *S. cerealella* was found to co-exist with *S. zeamais* for 8 years in 5.36 t of maize, 30-cm deep and stored under natural conditions (Arbogast and Mullen, 1987). The population growth of *S. zeamais* was probably constrained by the parasitic wasps *Anisopteromalus calandrae* (Howard) and *Cheotospila elegans* (Westwood) which were present in the grain habitat. No moth enemies were recorded. However, there is a conflicting report based on field experiments conducted in Mexico, indicating a high correlation between *S. cerealella* and *A. calandrae* as evidenced by the synchrony in the fluc-

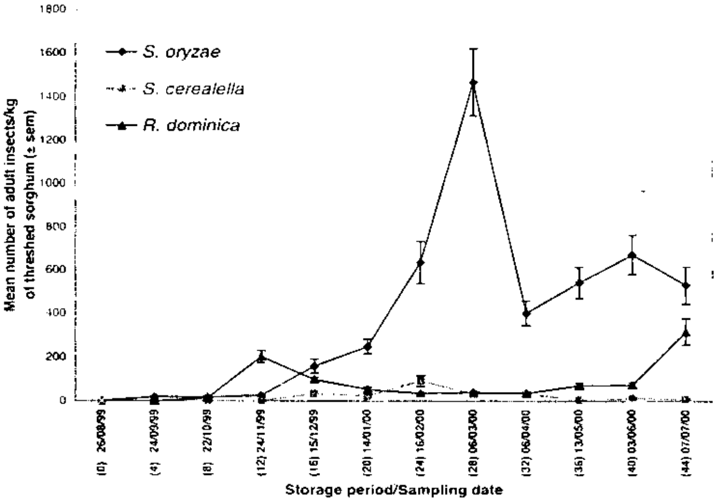

Fig. 19. Mean number of F1s, irrespective of sampling position, after a 5-week incubation of threshed sorghum from Binga stores (year 2; $n = 10$)

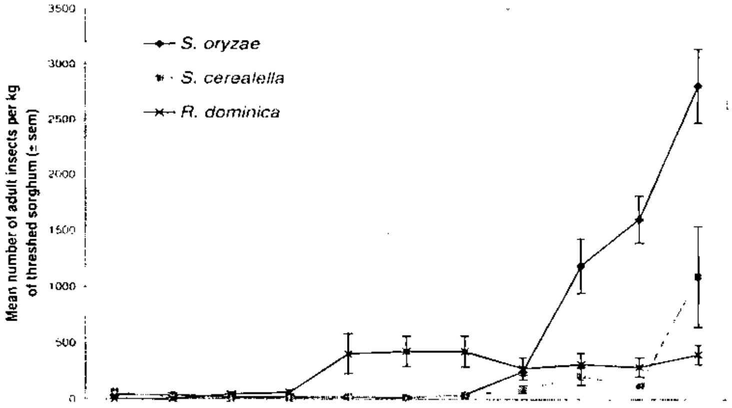

Fig. 20. Mean number of insects on unthreshed sorghum (all sampling positions) sampled from Binga stores (year 2; $n = 4$)

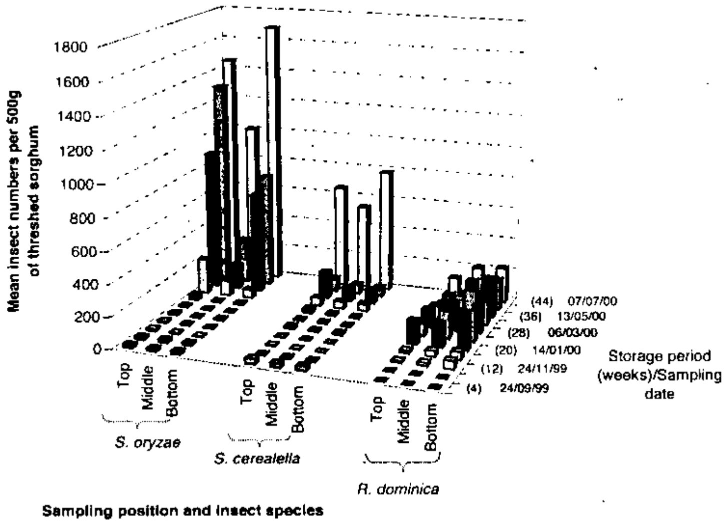

Fig. 21. Population distribution of *S. oryzae*, *S. cerealella* and *R. dominica* on unthreshed sorghum sampled from 3 depths in Binga stores (year 2, $n = 10$)

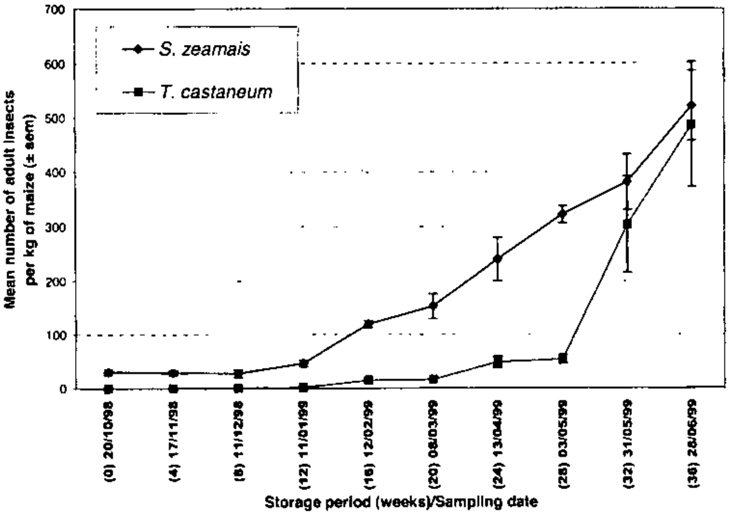

Fig. 22. Mean total number of adult insects (all sampling positions) on maize sampled from Harare stores (year 1; $n = 4$)

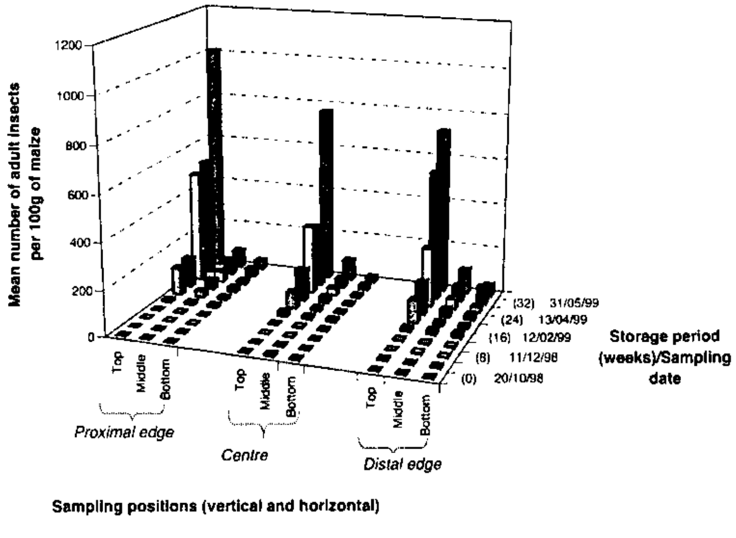

Fig. 23. Mean total number of insect pests in maize grain sampled from 3 depths and 3 horizontal positions in Harare stores (year 1; $n = 4$)

tuations of the two populations (Rios Ibarra et al., 1992). Therefore, the relationship between these two insects still needs to be objectively verified. *Anisopteromalus calandrae* were found at the two sites in the current study, but because of the low populations the nature of the relationship with *S. cerealella* could not be established.

As infestation pressure became severe in the top layer and food was exhausted, secondary pests such as *Cryptolestes ferrugineus* (Stephens) and *T. castaneum* or *Oryzaephilus surinamensis* L. became more successful at exploiting the damaged grain, resulting in a high total insect population in the top layer. The increased productivity of *T. castaneum* and *O. surinamensis* in maize grain colonised by *S. cerealella* has been reported (Weston et al., 2000). Because of the intense intra- and inter-species competition in the top grain layers, *Sitophilus* spp. gradually dispersed to lower grain layers in pursuit of food and space. However, because of the poor penetration ability of *S. cerealella* in threshed grain, it is likely that this species was forced to emigrate or could have been attacked by its natural enemies, including predation by *T. castaneum*.

Laboratory predation of *S. cerealella* by *T. castaneum* has been reported on sorghum (Shazali, 1982), and because of the strong aggregation tendencies of the two species in the top grain layers, there is a high chance that the beetle can cause substantial reduction of the moth population. However, during year 2 in Binga, this relationship was distorted by the presence of large numbers of *Xylocoris* sp. which is known to prey on *T. castaneum* (Haines, 1991). Hence, the potential effect of *T. castaneum* on *S. cerealella* was masked. The moth has a habit of resting on surfaces in the store compartment, particularly the walls, making it vulnerable to lizards and geckos which were observed feeding on the adult moths. Spiders also trapped large numbers of the moths in their webbing.

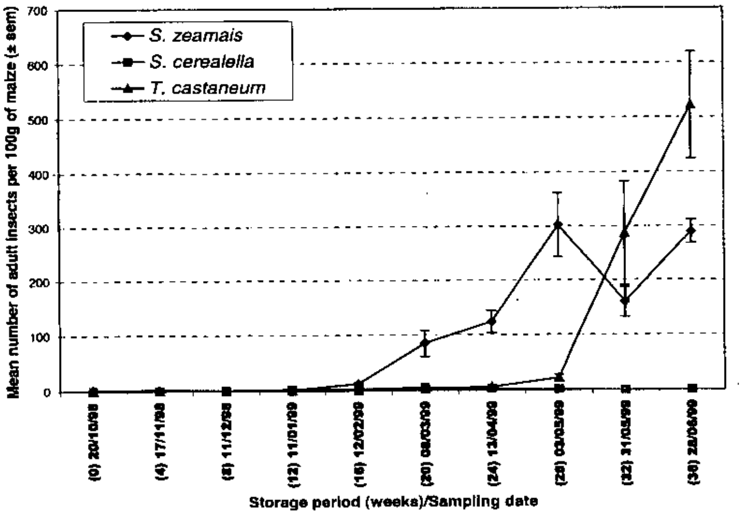

Fig. 24. Mean number of adult insects on maize sampled from the top layer in Harare stores (year 1; $n = 12$)

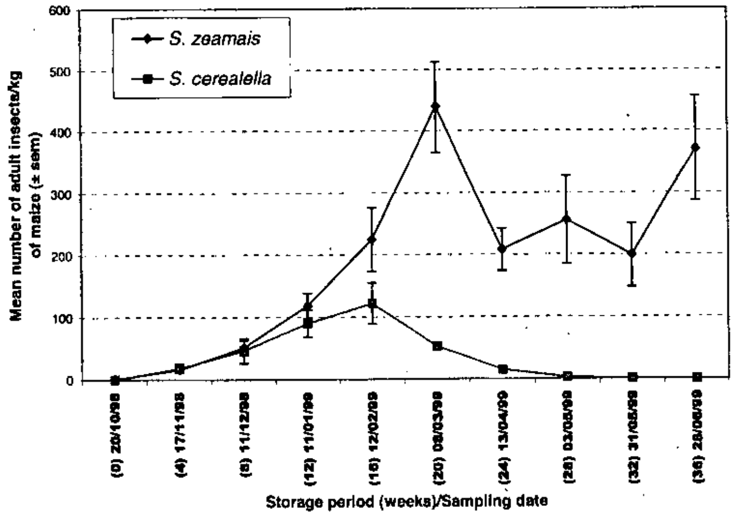

Fig. 25. Number of F1s (all sampling positions) after a 5-week incubation of maize sampled from Harare stores (year 1; $n = 4$)

Effect of physical environment

In Harare, the temperature within the maize grain was not a limiting factor for development of the moth, but the ambient temperature was. It is likely that *S. zeamais* could avoid unfavourably low temperatures at night by moving deeper into the grain (where it is warmer) which *S. cerealella* could not easily do because of its morphology.

The optimum temperature range for development of *S. cerealella* is 26–30°C, with the upper and lower limits being 35°C and 15°C (Howe, 1965; Haines, 1991). Conditions in Binga were conducive for insect development throughout the storage period. Generally, temperature alone cannot account for the poor performance of the moth, particularly on maize in Harare. Apart from the favourable temperature range, *S. cerealella* is also known be more prolific on sorghum than maize (Agha, 1961; Shazali, 1990), which could account for the differences in the abundance of the insect between the two areas.

In Zimbabwe, the grain storage season is typically preceded by at least 3 dry months, resulting in a slow insect population build-up at the beginning of the storage season. Low grain moisture content discourages insect breeding even when temperatures are favourable. The insect populations started increasing significantly in response to increased relative humidity in December, when the rainy season had commenced.

Grain damage and insect distribution

Most of the insects and the consequent damage evident after 5 months in storage were found in the top 30 cm of

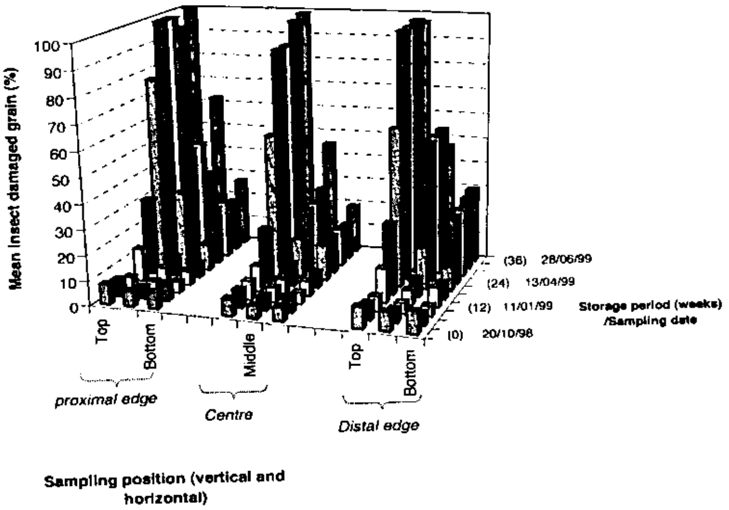

Fig. 26. Mean percentage of insect-damaged maize grain sampled from 3 horizontal positions and 3 depths in Harare (year 1; $n = 4$)

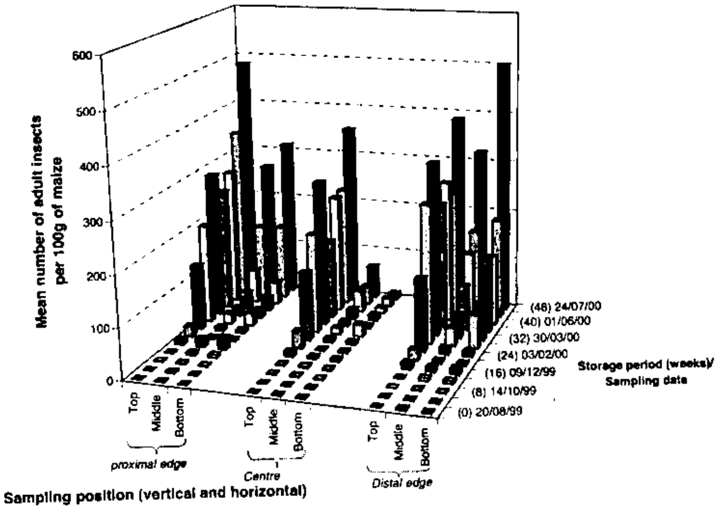

Fig. 27. Distribution of *S. zeamais* at 3 horizontal sampling positions and 3 depths on maize grain stored in Harare stores (year 2; $n = 10$)

threshed grain. Several factors could influence insect distribution either alone or in combination. These include: grain moisture content; grain temperature; presence and distribution of chaff and broken grains; insect inter- and intra-species interactions (Muir and White, 2000); and possibly bulk grain pressure. The question that remains is what exactly triggers the movement of the insects to specific locations in grain? According to Surtees (1964; 1965), storage insects move randomly with no directional bias and the motion disturbs neighbouring individuals, resulting in a general upward dispersal pattern; the disturbance factor being a function of weight and speed of movement of the individual insects involved. What remains unknown is why the insects would move up only and not down when "disturbed" by other insects. Surtees also postulated that insect species concentrate in certain grain zones in response to restrictive environmental factors such as temperature and grain moisture content, where there is minimum disturbance amongst individuals resulting in accumulation. One other factor Surtees pointed out, was that the presence of a physical boundary in grain such as a wall, elicits a thigmotactic response in insects, and thus contributes to the aggregation behaviour in certain zones. However, he did not specifically discuss the possible role of sex and aggregation pheromones in determining distribution patterns; an issue raised by Muir and White (2000). Aggregation of insects within a specific microhabitat may be a response to chemical stimuli.

The edge effect was significant only in maize towards the later part of the prolonged storage season (of up to 48 weeks) but was detected after 24 weeks. At low populations, *Sitophilus* spp. have a propensity to remain in contact with a vertical surface when they encounter it and disperse only after a certain critical density has been reached which creates overcrowded conditions (Surtees, 1964; 1965). The lack of significant effect on threshed sorghum may be due to the relatively large distances that insects have to travel around grains (which are densely packed), before they make contact with vertical walls. It could also be due to the fact that the

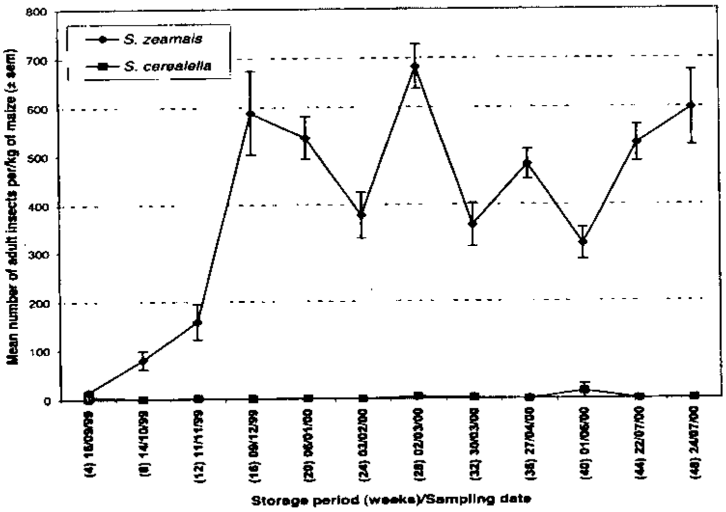

Fig. 28. F1 emergence (all sampling positions) after incubating maize sampled from Harare stores (year 2; $n = 10$)

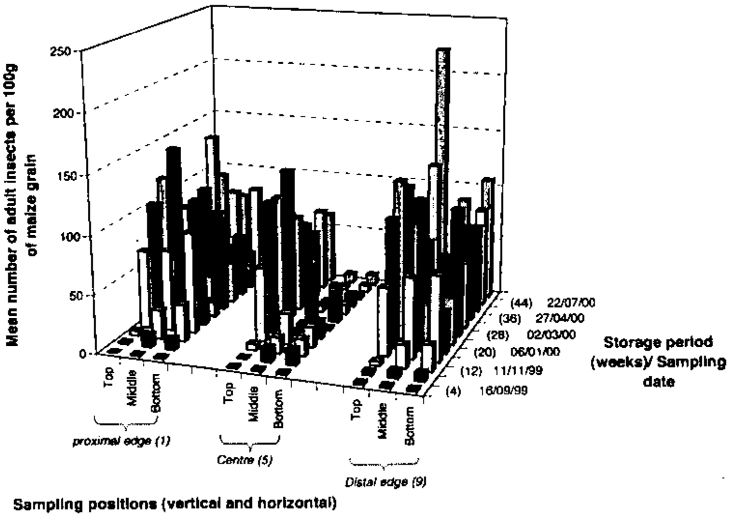

Fig. 29. Distribution of F1 *S. zeamais*, after a 5-week sample incubation, at 3 horizontal sampling positions and 3 depths on maize grain stored in Harare stores (year 2; $n = 10$)

edge sampling position was not sufficiently close to the walls to detect the presence of the insects. There were practical limitations in sampling any closer to the walls than the 10 cm used in this study. Edge infestation highlights the need for interior surface treatment of the compartment walls when applying grain protectants to grain, especially when storing maize for at least 6 months when the edge effect was exhibited.

The high grain temperature recorded at the middle position in maize at IAE could be a contributory factor in dispersal of insects, particularly to the edges where temperatures were comparatively lower as from week 12. This effect was more pronounced in year 2 when the edge effect was also highly significant from week 24 up to the end of the storage season.

Considering that the grain was initially fumigated, and that insect seeding was on the grain surface in the compartments, the occurrence of *R. dominica* or *Sitophilus* spp. in the middle and bottom layers imply that it was a result of downward dispersal of the insects. This is confirmed by the incubation results, which demonstrate that oviposition and multiplication of the beetles did take place in the middle and bottom grain layers.

The only major species that did not exhibit a strong tendency to aggregate in the top layer was *R. dominica*. The speed of response to a stimulus is important in regulating insect dispersal. Surtees (1965) reports that *R. dominica* move slowly and disturbance between individual insects is not sufficient to trigger upward movement by a large number of the insects; consequently, the author observed no aggregation in the upper layers. This means that once *R. dominica* move down to the lower grain layers, the greater part of the population tends to stay there. The implication is that any target treatment that may be implemented must take into consideration the dispersal behaviour of the beetle.

Conclusions

Sitotroga cerealella was dominant on unthreshed sorghum and can therefore compete favourably with *S. oryzae* and *R. dominica*, unlike on bulk grain where the moth was a poor competitor. It is unlikely that the poor performance of *S. cerealella* on maize was due solely to competition from *S. zeamais*. Parasitism by wasps and predation by *T. castaneum* are also likely to be major contributory factors.

On threshed grain:

- significantly higher insect numbers and resultant grain damage were found in the top 30-cm grain layer.
- relatively large numbers of *R. dominica* tended to occur in the middle and bottom layers, and *S. cerealella* is therefore more likely to be able to co-exist with the former species.
- the edge effect occurred only after prolonged storage (of at least 24 weeks), and on maize only; and
- natural enemies must be augmented if they are to effect control of pest populations.

The spatial and temporal distributions of insects found in this study have important implications for pest management in terms of targeting treatment to "hot" zones in order to reduce the amount of pesticide per unit mass of stored grain and ultimately the cost of grain treatment to the farmer.

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